Available online at www.sciencedirect.com

SCIENCE DIRECT

Remote Sensing of Environment 94 (2005) 187–203

Remote Sensing of Environment

www.elsevier.com/locate/rse

Quantifying the uncertainty in passive microwave snow water equivalent observations

James L. Foster[a,*], Chaojiao Sun[b,c], Jeffrey P. Walker[d], Richard Kelly[a,c], Alfred Chang[a], Jiarui Dong[a,c], Hugh Powell[a,e]

[a]*Code 974, Hydrological Sciences Branch, Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA*
[b]*Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA*
[c]*Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore, MD 21250, USA*
[d]*Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Victoria, 3010 Australia*
[e]*Science Applications International Corporation, 4600 Powder Mill Road, Beltsville, MD 20705, USA*

Received 2 February 2004; received in revised form 9 September 2004; accepted 11 September 2004

Abstract

Passive microwave sensors (PM) onboard satellites have the capability to provide global snow observations which are not affected by cloudiness and night condition (except when precipitating events are occurring). Furthermore, they provide information on snow mass, i.e., snow water equivalent (SWE), which is critically important for hydrological modeling and water resource management. However, the errors associated with the passive microwave measurements of SWE are well known but have not been adequately quantified thus far. Understanding these errors is important for correct interpretation of remotely sensed SWE and successful assimilation of such observations into numerical models.

This study uses a novel approach to quantify these errors by taking into account various factors that impact passive microwave responses from snow in various climatic/geographic regions. Among these factors are vegetation cover (particularly forest cover), snow morphology (crystal size), and errors related to brightness temperature calibration. A time-evolving retrieval algorithm that considers the evolution of snow crystals is formulated. An error model is developed based on the standard error estimation theory. This new algorithm and error estimation method is applied to the passive microwave data from Special Sensor Microwave/Imager (SSM/I) during the 1990–1991 snow season to produce annotated error maps for North America. The algorithm has been validated for seven snow seasons (from 1988 to 1995) in taiga, tundra, alpine, prairie, and maritime regions of Canada using in situ SWE data from the Meteorological Service of Canada (MSC) and satellite passive microwave observations. An ongoing study is applying this methodology to passive microwave measurements from Scanning Multichannel Microwave Radiometer (SMMR); future study will further refine and extend the analysis globally, and produce an improved SWE dataset of more than 25 years in length by combining SSMR and SSM/I measurements.
Published by Elsevier Inc.

Keywords: Snow cover; Snow water equivalent; Passive microwave; Uncertainty; Observation errors; SMMR; SSM/I

1. Introduction

Snow plays an important role in the global energy and water budgets, as a result of its high albedo and thermal and water storage properties. Snow is also the largest varying landscape feature of the Earth's surface. For example, in North America, the snow cover extent may vary from greater than 50% to less than 5% in the course of six months (Hall et al., 2002), and the snow water equivalent (hereafter referred to as SWE) of mid-latitude snowpacks can be reduced by as much as 100 mm in less than 6 days. Furthermore, snow depth and SWE, as well as snow cover extent, are important contributors to both local and remote climate (Gong et al., 2004). Thus, knowledge of snow

* Corresponding author. Tel.: +1 301 614 5769; fax: +1 301 614 5808.
E-mail address: James.L.Foster@nasa.gov (J.L. Foster).

0034-4257/$ - see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2004.09.012

extent and SWE are important for climate change studies and applications such as flood forecasting.

Despite its importance, the successful forecasting of snowmelt using atmospheric and hydrologic models is challenging. This is due to the imperfect knowledge of snow physics and simplifications used in the model, as well as errors in the model forcing data. Furthermore, the natural spatial and temporal variability of snow cover is characterized at space and time scales below those typically represented by models. Snow model initialization based on model spin-up will be affected by these errors. By assimilating snow observation products into land surface models, the effects of model initialization error may be reduced (Sun et al., 2004).

A critical requirement for successful assimilation of snow observations into models is an accurate knowledge of the observation errors. While it is possible to directly replace modeled states with observed states, this does not take into account the fact that model predictions and remotely sensed observations contain different amounts of error. In state-of-art data assimilation, error statistics of the observational data are required so that the correct weighting between observations and model estimates may be applied. Furthermore, in order for the remotely sensed SWE observations to be useful for climate modelers, water resource managers, and flood forecasters, it is necessary to have a quantitative, rather than qualitative, estimate of the uncertainty. A framework is needed to estimate SWE and its associated errors over large geographic areas.

In situ SWE data are poorly distributed globally and collected irregularly (Robinson et al., 1993). Passive microwave remote sensors onboard satellites provide an all-weather global SWE observation capability day or night. Brightness temperatures from different channels of satellite passive microwave sensors (hereafter referred to as PM) can be used to estimate SWE (or snow depth with knowledge of the snow density), and hence snow cover extent. This is a significant advantage over infrared sensors, which only work under cloud-free conditions, and visible sensors, which also require daylight to observe terrestrial features. More importantly, PM sensors provide estimates of the snow mass and not just snow cover extent. However, there are errors associated with the PM measurements. In order for the remotely sensed SWE observations to be useful for climate modelers, water resource managers, and flood forecasters, it is necessary to have both an unbiased SWE estimate and a quantitative, rather than qualitative, estimate of the uncertainty. This is a critical requirement for successful assimilation of snow observations into land surface models.

For most PM algorithms, the effects of vegetation cover and snow grain size variability are the main source of error in estimating SWE. Of lesser concern are the effects of topography and atmospheric conditions. A major assumption made in a number of PM algorithms is that vegetation cover does not affect the SWE estimates. In fact, it can have a significant impact on the accuracy of SWE estimates. In densely forested areas, such as the boreal forest of Canada, the underestimation of SWE from retrieval algorithms can be as high as 50% (Chang et al., 1996). Other factors such as topography and ice crusts effect PM retrievals but to a lesser extent than forests and crystal size.

The purpose of this paper is to explore a methodology for deriving unbiased PM SWE observations and associated uncertainty estimates. Errors due to simplifying assumptions of the retrieval algorithm are quantified. The 1990–1991 snow season is examined in detail as an example. PM SWE data from Special Sensor Microwave/Imager (SSM/I) for this snow season and their associated uncertainty are analyzed throughout North America. SSM/I data from seven snow seasons (from 1988 to 1995) are examined to evaluate our approach and validate our algorithm. We have focused on North America due to the availability of extensive in situ SWE data and abundance of field campaigns relative to the rest of the world. A future study will extend our analysis globally.

8. Conclusions

We propose a new passive microwave SWE retrieval algorithm based on the original algorithm by Chang et al. (1987) that accounts for the effect of vegetation cover and snow morphology in the North America. The contributions to the microwave response of snow by various factors are examined and evaluated. Dense vegetation is shown to be the major source of systematic error in the old algorithm; the assumption of constant snow grain size also contributes significant errors. Simplified empirical formulas are used to quantify the impact of vegetation cover and grain size growth during the snow season.

The results have been evaluated in tundra, taiga, prairie, alpine, and maritime Sturm classes in Canada using in situ SWE data from the Meteorological Service of Canada. The new algorithm reduces known biases in the old algorithm in most areas (particularly in taiga) and is shown to capture the accumulation and ablation phases of snow season well. The snow season during 1990–1991 is used as a case study. Seven snow seasons from 1988–1995 are evaluated. There is still some difficulty with the alpine and maritime Sturm classes, and partially forested areas. Recent field campaigns such as CLPX will help improve the parameterization of the passive microwave SWE retrievals. The improved spatial resolution and expanded range of channels at lower frequencies of the AMSR-E instrument will help curb the problems associated with mixed pixels and enhance the detection of shallow snowpacks.

We applied a methodology based on error estimation theory to quantify SSM/I SWE retrieval errors when using the new algorithm (9). The assessment of impact by forest cover and snow grain size are empirical based on our understanding of the nature of passive microwave emission from the ground. These empirical formulas need to be rigorously validated and updated when more extensive and accurate in situ observations become available; nonetheless, the methodology proposed here provides a means to evaluate the uncertainty in passive microwave SWE retrievals. Future study will investigate global application of our methodology and extend back to SSMR data (1979) to produce a long time series (over 25 years) of PM SWE data and coherent error estimates.